A SKIN FRICTION BALANCE

Eugene S. McVey*
Professor
Non-Member ASME

James W. Moore*
Associate Professor
Member ASME

INTRODUCTION

The measurement of in-flight skin friction drag on hypersonic aerodynamic bodies requires that measurement instruments be subjected to extreme environmental conditions. In addition to a severe vibration field, a skin friction meter may be subjected to a rapidly changing temperature environment which varies from a few degrees Rankine (due to liquid hydrogen lines) to 2000°F or more. A skin friction meter is expected to operate in a vehicle traveling at relatively high Mach numbers and at altitudes in excess of 100,000 feet. Mounting space near the vehicle skin is usually at a premium for measurement instrumentation so it is desired to keep package dimensions near the skin to two inches in thickness or less.

Little information is available from the literature to guide the design of a skin friction meter for high temperature environments, although Kistler Instrument Incorporated[1] claim operation to 1500°F for a skin friction meter they have developed. This performance is obtained by enclosing the meter in a cooling jacket to overcome the high temperature problem. Available information indicates that Kistler uses a closed loop null balance system to measure drag on a small section of skin which is free to move parallel to the skin surface. Fenter and Lyons[2] have reported on a skin friction meter developed to make measurements on Arobee-Hi Rockets. In a comprehensive report they describe an open loop system which uses a flexure to constrain a test segment of the missile skin. A linear variable dirrerential transformer (LVDT) is used

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*Both with the School of Engineering and Applied Science, University of Virginia, Charlottesville, Virginia. The research on which this paper is based was supported by the Force Measurements Section of the Instrument Research Division of NASA, Langley, Virginia, on NASA Grant NGR 47-005-026.

to measure flexure displacement and provide a read-out signal since displacement is proportional to friction drag.

A basic system is described in this paper which operates satisfactorily at room temperature and is believed to be capable of operating to 2000^{0}F with the substitution of a few critical high temperature components. Preliminary data have been taken to 900^{0}F on components developed for high temperature operation, and continuous operation of these components in a 2000^{0}F environment is anticipated by substituting special materials in the basic construction. The sensor and motor are located in the hot environment while the amplifier segment of the control loop is placed in a remote, cool location. Basic theory and low temperature experimental results will be presented here even though a high temperature capability has been the main concern in the general approach to the problem and in the design because this information should be of value to others working in the area in view of the fact that little or no related information is available in the literature. High temperature performance will be reported when the data are complete.

SYSTEM OPERATION AND ANALYSIS

A closed loop system configuration was chosen[3,4] which works on a null balance principle. The system is shown schematically in Fig. 1 and its block diagram is contained in Fig. 2. When a skin friction force, F_x, is present the flexure is displaced. The displacement is sensed by a transducer (e.g. an LVDT for translational motion) which has an output voltage proportional to displacement The sensor output is amplified and used to drive a motor which produces a force in opposition to the skin friction force. Motor armature current is measured and recorded because it is proportional to motor force. With proper design the measurements can be made essentially independent of both the motor flexure constant and changes in system gain due to other parameter changes as will be demonstrated.

The linear differential equation for the flexure and its associated inertia is

$$dF_x + \ell F_m - K_f\theta = J\ddot{\theta} \qquad (1)$$

where: F_x is skin friction drag;

K_f is the flexure constant;

J is the rotational inertia of all moving parts;

d is the distance from the tangent to the flexure;

ℓ is the distance from the servo motor to the flexure;

θ is flexure displacement angle.

K_m is the motor gain constant

It follows that

$$\theta(s) = \frac{dF_x(s) + \ell F_m(s)}{J(s^2 + K_f/J)} \tag{2}$$

The motor force is

$$F_m = K_m i_a \tag{3}$$

where K_m is the motor force constant. The motor armature voltage is

$$e_a = i_a R_a + K_v \ell \dot{\theta} \tag{4}$$

for small deflection angles and negligible armature inductance. Both assumptions are very good here. For example, the total motor deflection is expected to be .0005 radian or less. The distance from the flexure to the motor is ℓ, and the motor back emf constant is K_v, and R_a is the armature circuit resistance. From Eq. (4)

$$i_a(s) = \frac{e_a(s) - \ell K_v s\theta(s)}{R_a} \tag{5}$$

The armature voltage will be the output of the sensor multiplied by the gain of the amplifier, K_a. For a translational type transducer with sensitivity constant K_s the transducer output is $\ell K_s \theta$. The amplifier must introduce a 180^0 phase shift so that the system will have negative feedback. Thus

$$e_a = - K_s \ell \theta K_a \tag{6}$$

From Fig. 2 the closed loop transfer function in terms of drag force and motor armature current (which is the read-out quantity) is

$$\frac{i_a(s)}{F_x(s)} = \frac{-d\ell K_v \left[s + \frac{K_s K_a}{K_v} \right]}{JR_a \left(s^2 + \frac{\ell K_m K_v}{JR_a} s + \frac{\ell^2 K_m K_a K_{(s)} + R_a K_f}{JR_a} \right)} \tag{7}$$

To demonstrate the relationship between the drag force and the motor current in the steady state, assume that a step of force F_x/s is applied to the system. In the steady state

$$i_{a,ss} = \lim_{s \to 0} s \left[\frac{F_x}{s} \left\{ \frac{i_a(s)}{F_x(s)} \right\} \right]$$

$$= \frac{-d\,\ell K_s K_a}{\ell^2 K_m K_s K_a + R_a K_f} F_x \tag{8}$$

by the final value theorem. If

$$\ell^2 K_m K_s K_a \gg R_a K_f \tag{9}$$

Eq. (8) may be written

$$i_{a,ss} = -\frac{F_x}{K_m} \frac{d}{\ell} \tag{10}$$

From Eq. (3) the value of $K_m i_a$ may be inserted to show that

$$F_m = -F_x \frac{d}{\ell} \tag{11}$$

Thus, by making the amplifier gain constant K_a sufficiently large the motor force nulls out the applied force and the motor current is a direct indication of drag force.

From Eq. (8) and Eq. (9) it is apparent that changes in system gain and changes in the flexure constant K_s do not affect system accuracy if the inequality of Eq. (9) is satisfied. Thus, it is desirable to make the amplifier gain, K_a, relatively large consistent with system stability. Experimental results have demonstrated that K_a can be made sufficiently large to make the relationship of Eq. (9) valid if stability compensation is added.

The greatest sources of error at high temperatures is anticipated to be due to variation of the motor force constant K_m and the position sensor zero position. The high temperature model motor, position transducer and flexure assembly have been designed to minimize errors due to thermal effects. Air core type construction has been used to avoid temperature dependent magnetic materials and to make K_m and K_s independent of temperature except for dimensional stability problems. This means that an electromagnetic motor field must be used at high temperature instead of a permanent magnet field as in the low temperature model.

In order to assure operation of the system in the ambient vibration and acceleration field as well as operation over a wide temperature range, it is necessary to pay particular attention to the form of pivots used for the moving parts. The pivots must hold the parts completely rigid against all motion, except for rotation about the measurement axis. To satisfy the requirements of the control system,backlash, stiction and hysteresis must be zero or very small. It would be preferable if the pivot exerted no rotational forces of its own, such as the spring constant K_f Eq. (1) ff, used in deriving the control equations.

The preceeding requirements indicated that the best pivot would probably be either an air bearing or a flexural pivot bearing. The latter was chosen for initial study because it is self-contained and because of its high rigidity about the non-rotational axes. To meet temperature requirements, it is necessary to use materials which have high strength at 2000^{0} F and which are not brittle at extremely low temperatures. Initial studies are being made using Haynes Alloy 25 as the flexure members.

The extremely small forces to be measured require that the spring constant of the flexure be very small relative to the control loop gain as shown by Eq. (9). Therefore a three member flexure will be used as diagrammed in Fig. 3a. By adjustment of the tension in the flexures the rotational spring constant can be made positive, negative or zero.

The environmental force field includes both translational and rotational vibrations and translational and rotational accelerations. In order for the control system motor to not need to overcome the effects of this field, the moving members are counterbalanced as shown in Fig. 3b. The two rotating members are each counterbalanced about their own axis. They are then coupled together by a flexure system so that they tend to rotate in opposite directions when an angular acceleration is applied to their common base. Thus; both translational and rotational inertia effects are cancelled.

EXPERIMENTAL RESULTS

An experimental model was built and tested at room temperatures. A Collins Manufacturing Co. LVDT 55-203 with a sensitivity of 1 volt per mil was used to measure flexure displacement. A Bendix, Inc. flexure Model No. 6016-800 was used (the experimental system was not counterbalanced) as the pivot. The motor consisted of a 0.125 inch diameter, 1.0 inch long piece of Alnico V mounted on the sting for the field and 2000 turns of No. 30 wire wound in a coil 1.5 inches long to form the armature of a solenoid motor. An operational amplifier followed by a unity gain power amplifier was used to obtain amplification and motor drive. The system parameters are:

K_a = 100 v/v	K_v = negligible
K_m = 43 lb/amp	R_a = 99 ohms
K_s = 0.5 v/mil	$J = 5.8 \times 10^{-5}$ ft lb sec^2
K_f = 0.8 in. lb./rad	ℓ = 3.3 cm

Uncompensated open loop frequency response data are shown in Fig. 4. As can be seen from the plot, the open loop gain constant is 225, a value which is high enough to allow relatively large variations in any system parameter except K_m without affecting calibration more than a fraction of a per cent. For example, the flexure constant varied 5 per cent when heated to 500^0 F. This change had negligible effect on the force reading.

The mechanical resonance makes it necessary to use lag compensation in such a manner that the resonant peak frequency is well above the crossover frequency. Lag compensation was used is this case because speed of response was not important.

A linearity curve is shown in Fig. 5. It is apparent that the system is linear to within 1 per cent. The repeatability was also found to be within 1 per cent at room temperature.

REFERENCES

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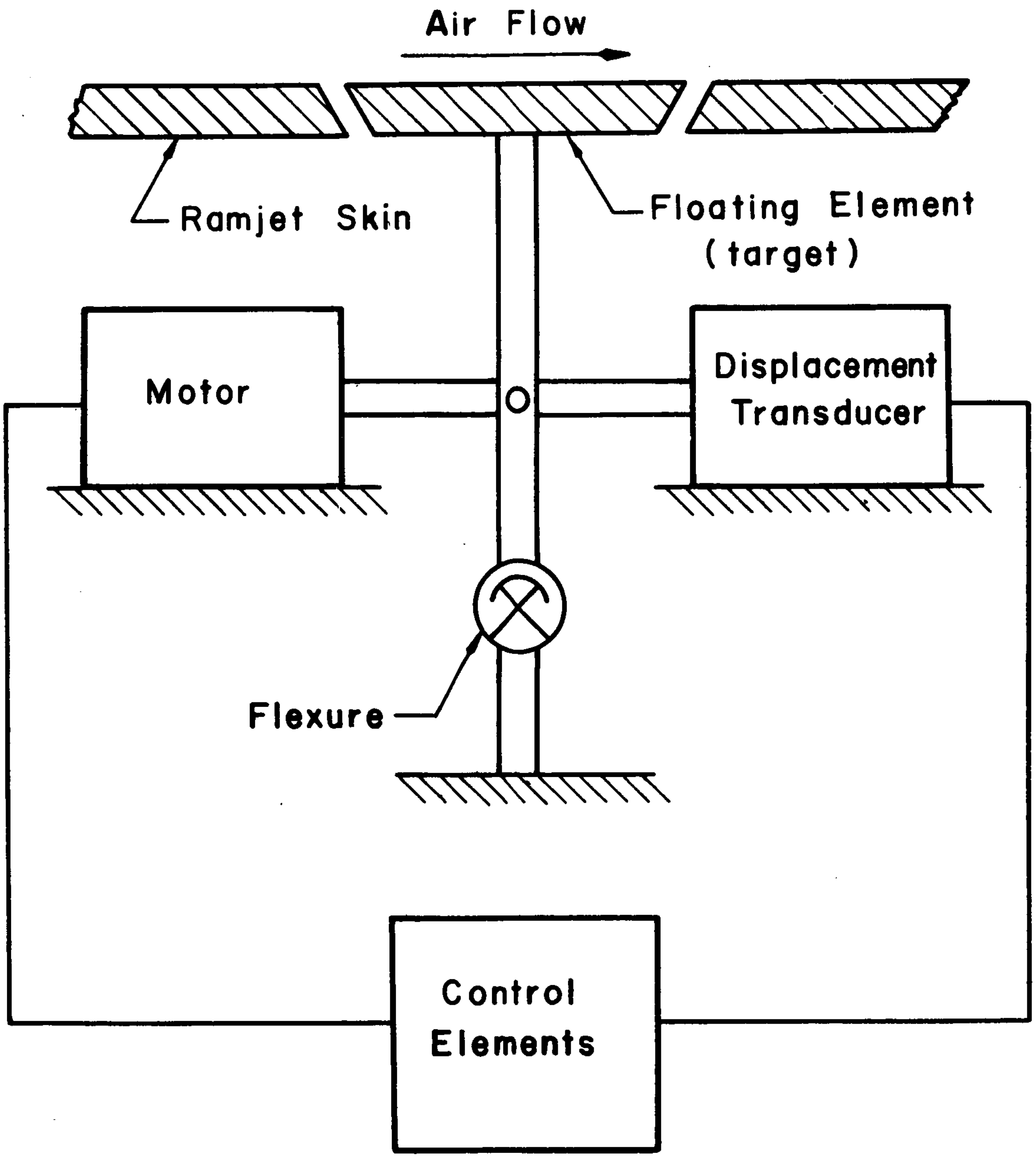

Air Flow
Ramjet Skin
Floating Element
(target)
Motor
Displacement
Transducer
Flexure
Control
Elements

Fig. I

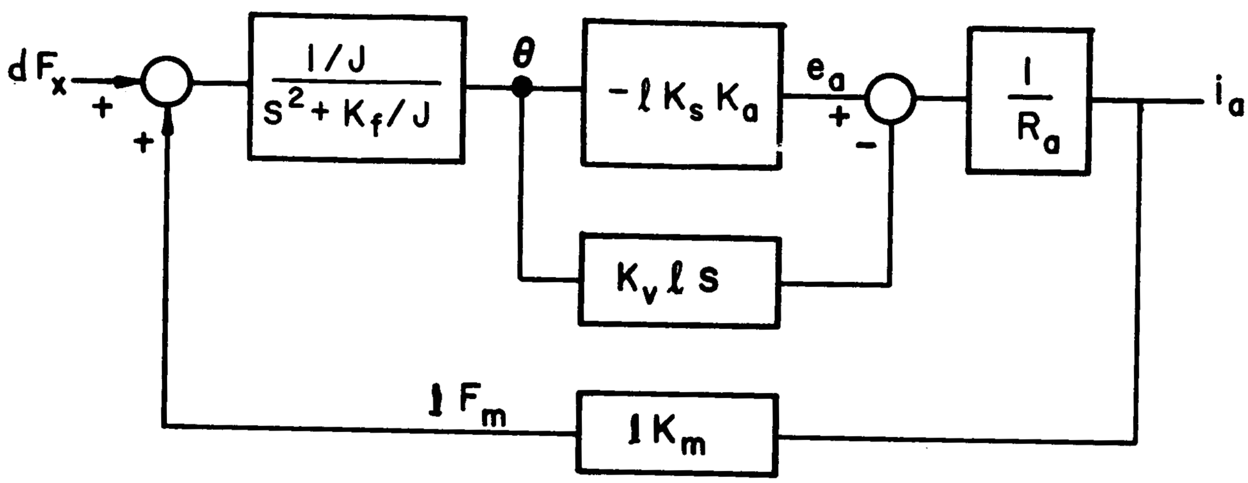


Fig. 2

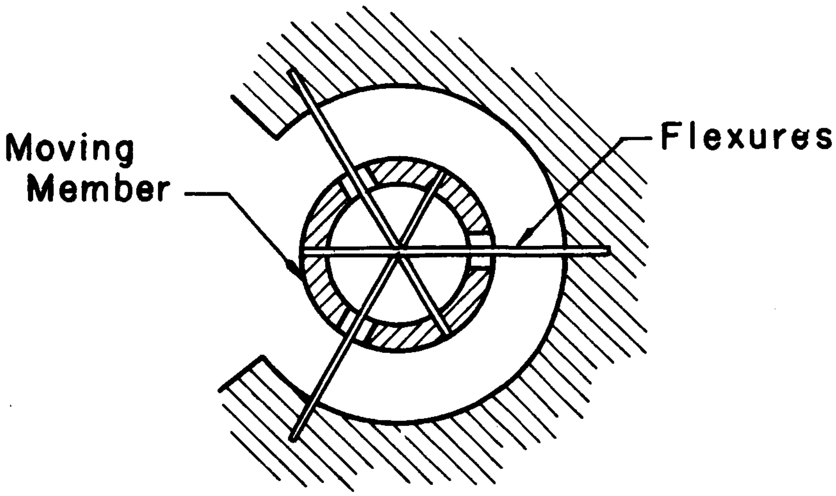

Moving
Member
Flexures

Fig. 3a

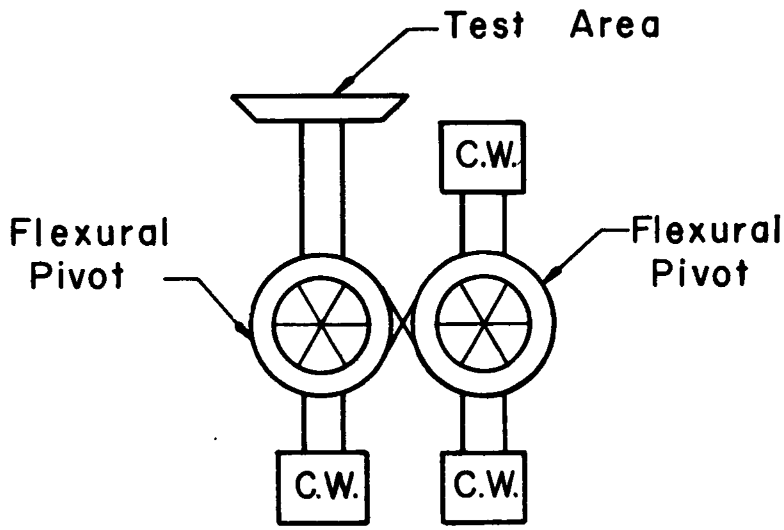

Test Area
C.W.
Flexural
Pivot
Flexural
Pivot
C.W.
C.W.

Fig. 3b

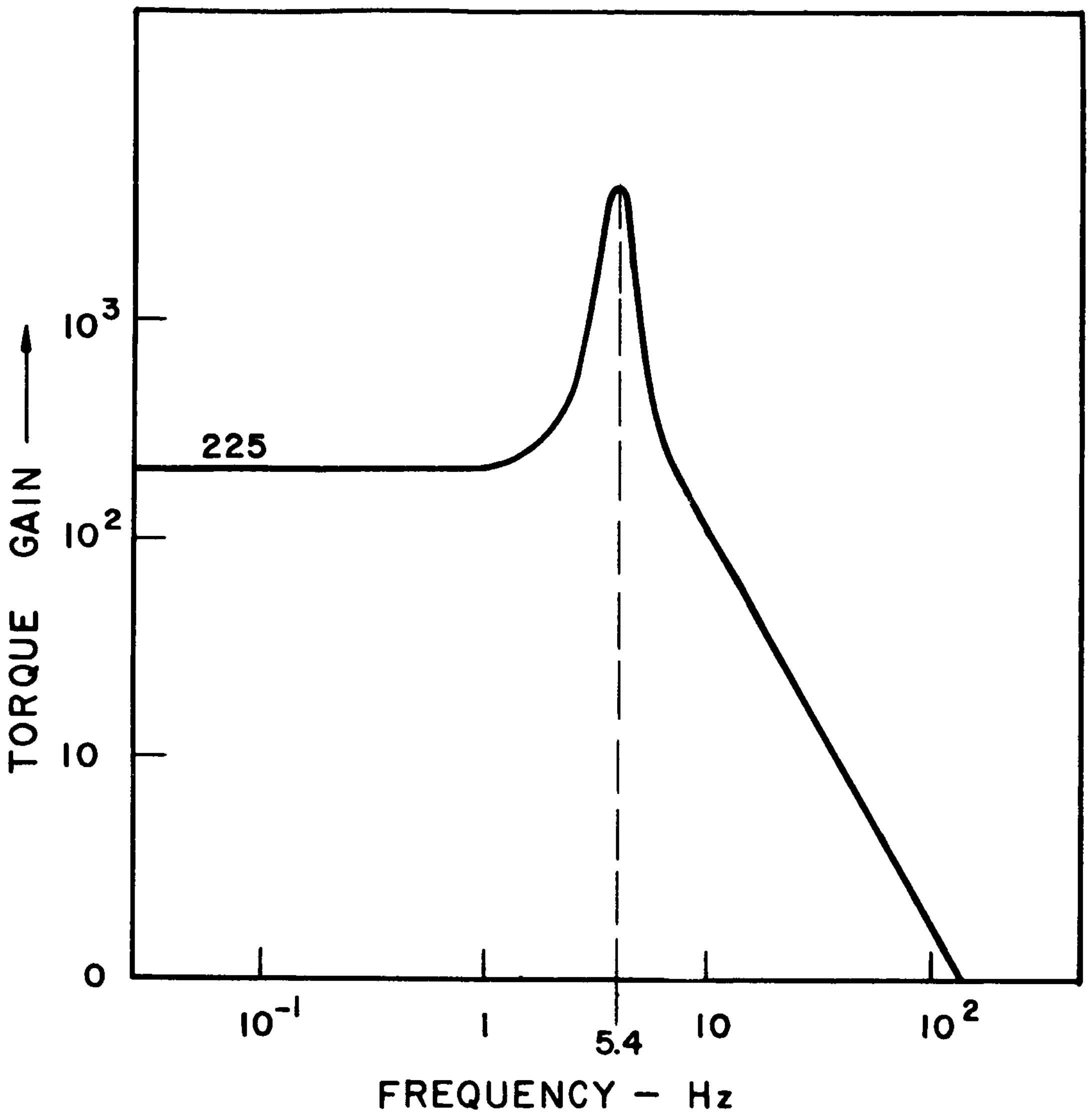
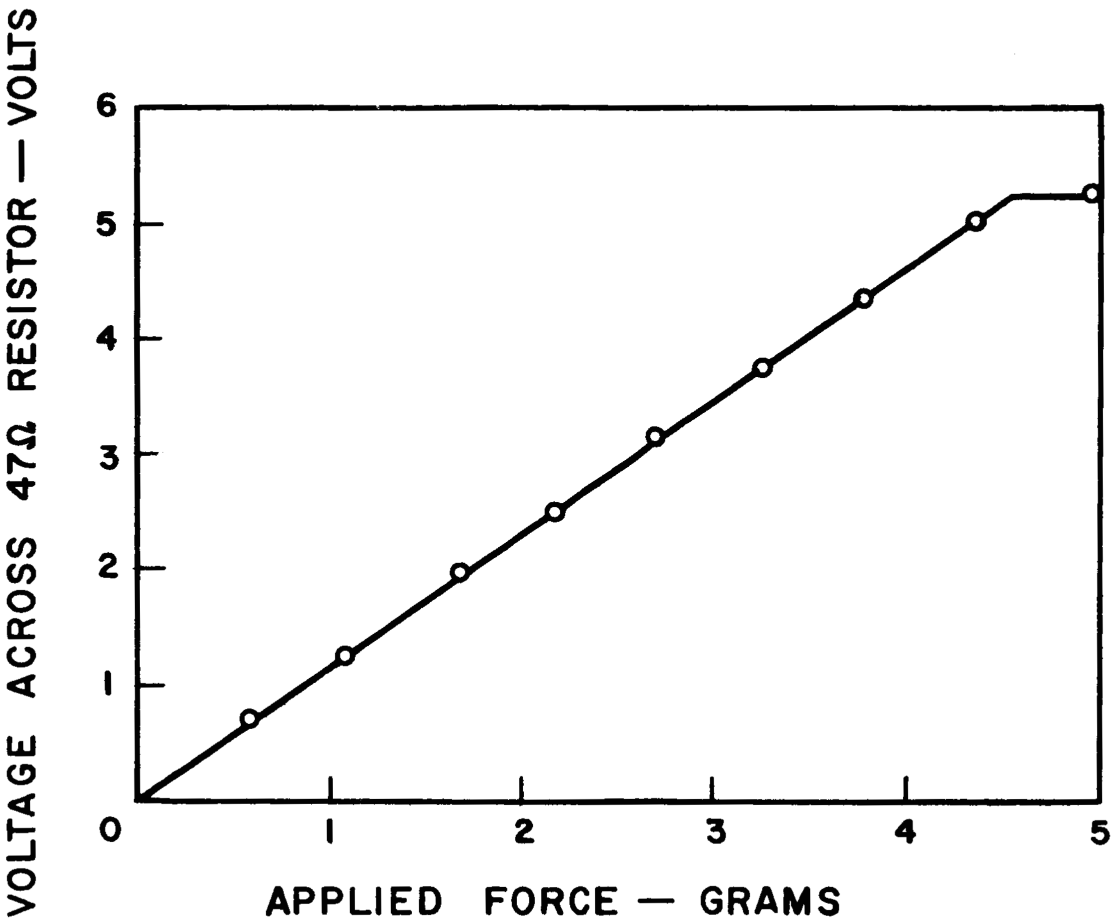


Fig. 4



VOLTAGE ACROSS 47Ω RESISTOR — VOLTS
6
5
4
3
2
1
0
1
2
3
4
5
APPLIED FORCE — GRAMS

Fig. 5